PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 :
G01R 33/032, 33/02

A1

(11) International Publication Number: WO 00/37952

(43) International Publication Date: 29 June 2000 (29.06.00)

(21) International Application Number: PCT/IB99/02079

(22) International Filing Date: 21 December 1999 (21.12.99)

(30) Priority Data:
9828189.2 21 December 1998 (21.12.98) GB

(71) Applicant (*for all designated States except US*): ABB AB [SE/SE]; S–721 83 Västerås (SE).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): NORLING, Fredrik [SE/SE]; Ankarets Väg 145, S–435 42 Mölnycke (SE). EKBERG, Mats [SE/SE]; Lansenvägen 13, S–187 62 Täby (SE). LEIJON, Mats [SE/SE]; Hyvlargatan 5, S–723 35 Västerås (SE).

(74) Agent: CARPMAEL, John, William, Maurice; Carpmaels & Ransford, 43 Bloomsbury Square, London WC1A 2RA (GB).

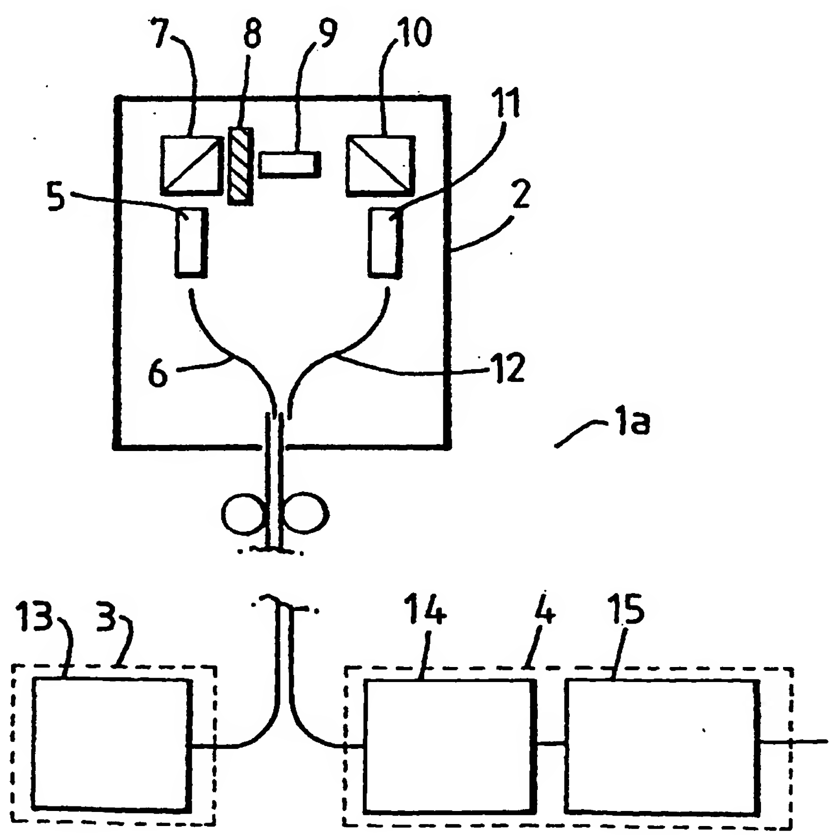
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: MAGNETIC FIELD SENSORS

(57) Abstract

A three–dimensional magnetic field sensing arrangement comprises three magnetic non–conducting sensors, e.g. (1a), arranged for sensing the three respective components of an external magnetic field. Each sensor comprises a sensor module (2), a transmitter module (3) containing a laser diode (13), and a receiver module (4) containing a photodetector (14) and a filter and amplifier (15). The sensor module (2) comprises in sequence a collimating lens (5), connected to an efferent optic fibre (6), a first polarising beam–splitter (7), a half–wave plate (8), a rare–earth–doped iron garnet Faraday–effect transducer (9), which rotates the plane of polarisation of the light through an angle which depends on the component of an external magnetic field in the propagation direction, a second polarising beam–splitter (10) and a focussing lens (11) connected to an afferent optic fibre (12). The invention finds particular application in measuring magnetic fields associated with electrical breakdown in high–voltage environments, for which sensors made from conductive materials are not suitable, as well as measuring any type of magnetic fields in environments with high electric fields and high voltages.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

MAGNETIC FIELD SENSORS

The present invention relates to magnetic field sensors, and in particular to such sensors which are arranged to sense all the three vector components of a magnetic field. The invention extends to corresponding methods of measurement of magnetic fields using such sensors.

A particularly advantageous application of such three-dimensional sensing arrangements would be in the measurement of the magnetic fields associated with electrical breakdown, since the direction of the magnetic field can be determined and thereby the source of the breakdown.

Known three-dimensional magnetic field sensors use nonmagnetic electrically-conductive coils, typically made of copper, in which the electric current induced by the magnetic field being measured is sensed, thereby to determine the three components of the magnetic field. However, such sensors could not be used in the above application, since such conductive sensors cannot safely be used near high-voltage cables because of the risk of electrical breakdown, i.e. arcing.

Magnetic field sensors are known which are made from magnetic, non-conducting material. Such sensors have the advantage of their ability to measure magnetic fields in environments with high electric fields and high voltages. However, such sensors have not been combined into a single sensing unit for detecting the three vector components of magnetic field, presumably because it would be considered that the magnetic material of each sensor would interfere with the measurements made by the other two sensors. However, the present inventor has found that the level of interference is surprisingly small.

Thus, in accordance with a first aspect of the present invention there is provided a three-dimensional magnetic field sensing arrangement comprising three magnetic field sensors each of which is arranged for sensing a respective one of three orthogonal components of the magnetic field to be measured, each sensor comprising a substantially non-conducting magnetic material.

In accordance with a further aspect of the present invention there is provided a method of measuring three orthogonal components of a magnetic field comprising arranging each of three magnetic substantially electrically non-conducting magnetic field sensors within the magnetic field for sensing a respective one of the three orthogonal components and thereby determining the magnitude and the direction of the magnetic field.

The magnetic field sensors are preferably substantially identical, since this will ensure that the sensor characteristics, i.e. the strength of the output signal for a given magnetic field component, are uniform.

Each sensor is advantageously a Faraday-effect sensor, since this provides a convenient arrangement in which no electrical leads are required in the region of the high-voltage apparatus, since light can be conveyed to each sensor from a remote location, e.g. using optic fibres. The use of separate optic fibres confers the advantage of substantially eliminating cross-talk between the outputs of the three sensors. In this case, the magnetic material constituting the Faraday-effect transducer is preferably ferrimagnetic, rare-earth-doped iron garnet, such as yttrium iron garnet (YIG). YIG has the advantage of being a good electrical insulator. However, any magneto-optic material displaying sufficiently low electrical conductivity may be used.

The optic fibres may be single-mode (SM), multimode (MM) or polarisation-maintaining (PM) optic fibres. Each sensor advantageously comprises at least one gradient index (GRIN) lens, since this removes the need for relatively large conventional collimating and focussing lenses to be provided within each sensor. Furthermore, each GRIN lens is preferably attached to a respective optic fibre to form what is known as a pigtail unit. Such units are commercially available and there is therefore no requirement for an elaborate alignment procedure for the sensors.

Each sensor preferably includes, in sequence, an efferent pigtail unit, a polarising beam-splitter, a half-wave plate, which rotates the plane of polarisation of plane-polarised light, a Faraday-effect transducer, a further polarising beam-splitter and an afferent

pigtail unit. By manually rotating the half-wave plate, the polarisation direction of the light can be adjusted to optimise the performance of the sensor.

A transmitter unit, comprising the three light sources, and a receiver unit, comprising the three photodetectors and circuitry, are preferably situated remotely from the magnetic field to be measured and thereby remotely from high-voltage sources. The light sources may each comprise a laser diode, and the electronic circuitry within the receiver unit may comprise three respective filters and corresponding amplifiers.

Although the radiation used in the Faraday-effect sensor is described herein as being light, it will be understood that the term "light" as used herein embraces additionally non-visible radiation of a wavelength suitable for effecting the required measurements.

A preferred embodiment of the present invention will now be described with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically the arrangement of one of the three sensors in the preferred embodiment;

Figure 2 illustrates the arrangement of the three sensors in the preferred embodiment; and

Figure 3 illustrates schematically the over-all arrangement of the magnetic field detector of the preferred embodiment.

Referring to Figure 1, a sensor 1a comprises a sensor module 2, a transmitter module 3 and a receiver module 4. The sensor module 2 comprises a first gradient index (GRIN) lens 5, connected to an efferent optic fibre 6, a first polarising beam-splitter 7 for polarising the light from the first GRIN lens 5 and reflecting the polarised light to a half-wave plate 8. Light from the half-wave plate 8 is directed to the Faraday-effect transducer 9, which is in the form of a block of yttrium iron garnet (YIG). Light passing through the transducer 9 then passes to a second polarising beam-splitter 10 and is reflected to a second GRIN lens 11 which is connected to an afferent optic fibre 12.

The sensor module 2 functions as follows. Light received via the efferent optic fibre 6 is collimated by the first GRIN lens 5 and plane-polarised by the polarising beam-splitter 7. The resulting plane-polarised light then passes through the half-wave plate 8, which serves to rotate the plane of polarisation of the polarised light by an amount dependent on the orientation of the plate. Light then passes into the block of YIG, which exhibits the property of rotating the plane of polarisation of the plane-polarised light though an angle the magnitude and direction of which depend in a known manner on the strength and the sense of the component of an external magnetic field in the propagation direction of the light. The second polarising beam-splitter 10 serves to analyse the light transmitted through the block of YIG into two polarisation components, one of which is supplied to the second, focussing GRIN lens 11, which then transmits the light to the afferent optic fibre 12. The amount of light deflected into the second GRIN lens by the polarising beam-splitter 10 will therefore depend on the strength of the component of the magnetic field in the direction of the propagation direction of the light through the block of YIG, and this can be measured to provide a measure of the strength of that magnetic field component.

The transmitter module 3 comprises a laser diode 13, which supplies monochromatic light to the efferent optic fibre 6.

The receiver module 4 comprises a photodetector 14 for receiving light from the afferent optic fibre 12 and electric circuitry in the form of a filter and amplifier 15 for filtering and magnifying the signal from the photodetector 14.

The optic fibres used as the efferent and afferent optic fibres 6, 12 may be single-mode (SM), multimode (MM) or polarising (PZ) optic fibres.

Referring to Figures 2 and 3, a complete detector 1 comprises three such sensors. Three sensor modules 2a, 2b, 2c are mounted together within a sensor housing 16 such that the three directions of light propagation in the Faraday-effect transducers 9 are mutually orthogonal. For example, sensor module 2a may be oriented so as to be sensitive to a magnetic field component in the x direction, 2b in the y direction and 2c in the z

direction, as indicated in Figure 2. A transmitter unit 17 houses three laser diodes for supplying monochromatic light to the respective three sensor modules 2a, 2b and 2c via three respective efferent optic fibres 6a, 6b, 6c. A receiver unit 18 houses three respective photodetectors, which receive light from the three respective afferent optic fibres 12a, 12b, 12c, and three sets of filters and amplifiers.

With a three-dimensional magnetic field detector of the preferred embodiment, as described above, it will be appreciated that it is possible to measure the three vector components of the magnetic field within high-voltage environments, without the risk of arcing through the detector, since there need be no electrical conduction path between the transducers, which must be located in the magnetic field to be measured, and the other components of the detection equipment, which are remotely situated. Furthermore, it would be possible to arrange for the detector to be scanned through a spatial region thereby to obtain a mapping of the magnetic field throughout a region of interest. From the three measured components, it is of course possible to measure the magnitude of the magnetic field and also the direction.

The spatial resolution of the detector depends upon the separation of the three transducer elements, but it is expected that the resolution will be better than 10mm. The magnetic field amplitude resolution of the detector will depend on the signal noise level, but it is expected that the resolution will be approximately equal to, or better than, 16 nT / $\sqrt{f}$, where f is the frequency in Hz. The temporal resolution is virtually unlimited, given that YIG exhibits a frequency response which surpasses the GHz region. In practice, the temporal resolution will be governed by the detection electronics and by the detection bandwidth, which also governs the noise level, which in turn affects the amplitude resolution.

Although a preferred embodiment of the present invention has been described above, many variations and modifications will be apparent to those skilled in the art, and the scope of the invention is defined solely by the claims appended hereto.

CLAIMS:

1. A three-dimensional magnetic field sensing arrangement comprising three magnetic field sensors each of which is arranged for sensing a respective one of three orthogonal components of the magnetic field to be measured, each sensor comprising a substantially electrically non-conducting magnetic material.

2. A magnetic field sensing arrangement as claimed in Claim 1, wherein the three sensors are substantially identical.

3. A magnetic field sensing arrangement as claimed in Claim 1 or Claim 2, wherein each sensor comprises a Faraday-effect sensor.

4. A magnetic field sensing arrangement as claimed in Claim 3, wherein each sensor comprises a Faraday-effect transducer, a respective light source and a photodetector, each said light source and each said photodetector being located in use remotely from the Faraday-effect transducer.

5. A magnetic field sensing arrangement as claimed in claim 4, wherein each sensor comprises a respective efferent optic fibre for conveying light from the light source to the transducer and a respective afferent optic fibre for conveying light from the transducer to the photodetector.

6. A magnetic field sensing arrangement as claimed in Claim 5, wherein at least one of the optic fibres is a single-mode optic fibre.

7. A magnetic field sensing arrangement as claimed in Claim 5 or Claim 6, wherein at least one of the optic fibres is a multimode optic fibre.

8. A magnetic field sensing arrangement as claimed in any one of Claim 5 to 7, wherein at least one of the optic fibres is a polarisation-maintaining optic fibre.

9. A magnetic field sensing arrangement as claimed in any one of Claims 5 to 8, wherein each sensor further comprises a respective first gradient index lens positioned in the optical path between the efferent optic fibre and a second respective gradient index lens positioned in the optical path between the transducer and the afferent optic fibre.

10. A magnetic field sensing arrangement as claimed in Claim 9, wherein each of said graded refractive index lenses is connected to the associated optic fibre in a pigtail unit.

11. A magnetic field sensing arrangement as claimed in any one of Claims 5 to 8, wherein each sensor comprises, in sequence, an efferent pigtail unit comprising said efferent optic fibre connected to a graded refractive index lens, a polarising beam-splitter, a half-wave plate, a Faraday-effect transducer, a further polarising beam-splitter and an afferent pigtail unit comprising a graded refractive index lens connected to said afferent optic fibre.

12. A magnetic field sensing arrangement as claimed in any preceding claim, wherein the magnetic material of each sensor is ferrimagnetic.

13. A magnetic field sensing arrangement as claimed in Claim 12, wherein the magnetic material of each sensor is a rare-earth-doped iron garnet.

14. A magnetic field sensing arrangement as claimed in Claim 13, wherein the magnetic material of each sensor is yttrium iron garnet.

15. A method of measuring three orthogonal components of a magnetic field comprising arranging each of three substantially electrically non-conducting magnetic field sensors within the magnetic field for sensing a respective one of three orthogonal components and thereby determining the magnitude and the direction of the magnetic field.

16. A magnetic field sensing arrangement substantially as hereinbefore described with reference to the accompanying drawings.

17. A method of measuring three orthogonal components of a magnetic field substantially as hereinbefore described with reference to the accompanying drawings.

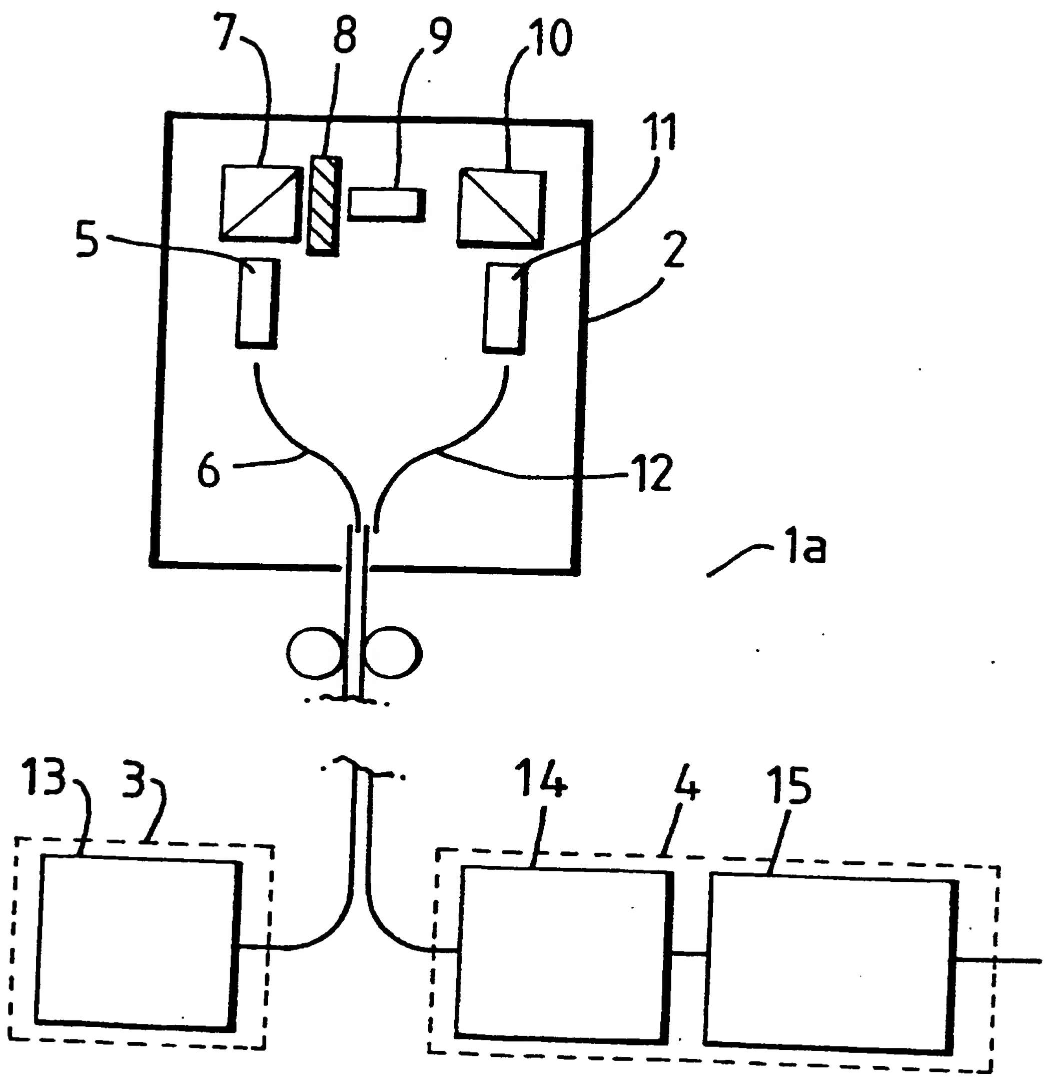


Fig. 1

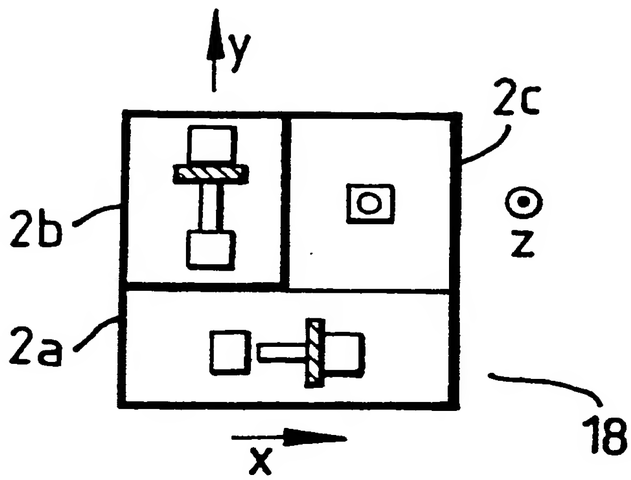


Fig. 2

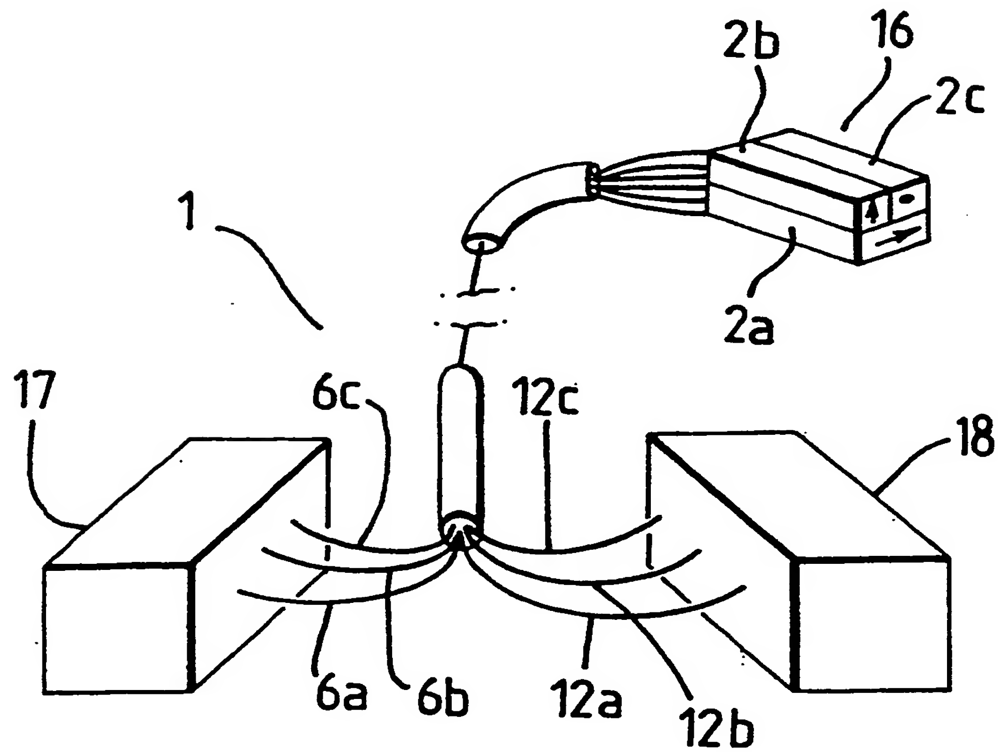


Fig. 3

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 99/02079

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01R33/032 G01R33/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 345 759 A (MATSUSHITA ELECTRIC IND CO LTD ;KANSAI ELECTRIC POWER CO (JP)) 13 December 1989 (1989-12-13) column 5, line 56 -column 6, line 46; figure 8 column 7, line 8 - line 34; figure 10	1-5,9-17
Y	US 4 450 406 A (BOBB LLOYD C) 22 May 1984 (1984-05-22) abstract	1-5,9-17
A	US 4 584 470 A (IIZUKA HISAO ET AL) 22 April 1986 (1986-04-22)	3-6,8
A	US 5 243 403 A (KOO KEE P ET AL) 7 September 1993 (1993-09-07) abstract	1,2

[ ] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 May 2000	17/05/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Haasbroek, J

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/IB 99/02079

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0345759 A	13-12-1989	JP 1312483 A	18-12-1989
		JP 2001232 C	20-12-1995
		JP 7031232 B	10-04-1995
		DE 68911992 D	17-02-1994
		DE 68911992 T	21-07-1994
		KR 9615986 B	25-11-1996
		US 5075546 A	24-12-1991
US 4450406 A	22-05-1984	NONE	
US 4584470 A	22-04-1986	NONE	
US 5243403 A	07-09-1993	NONE	